

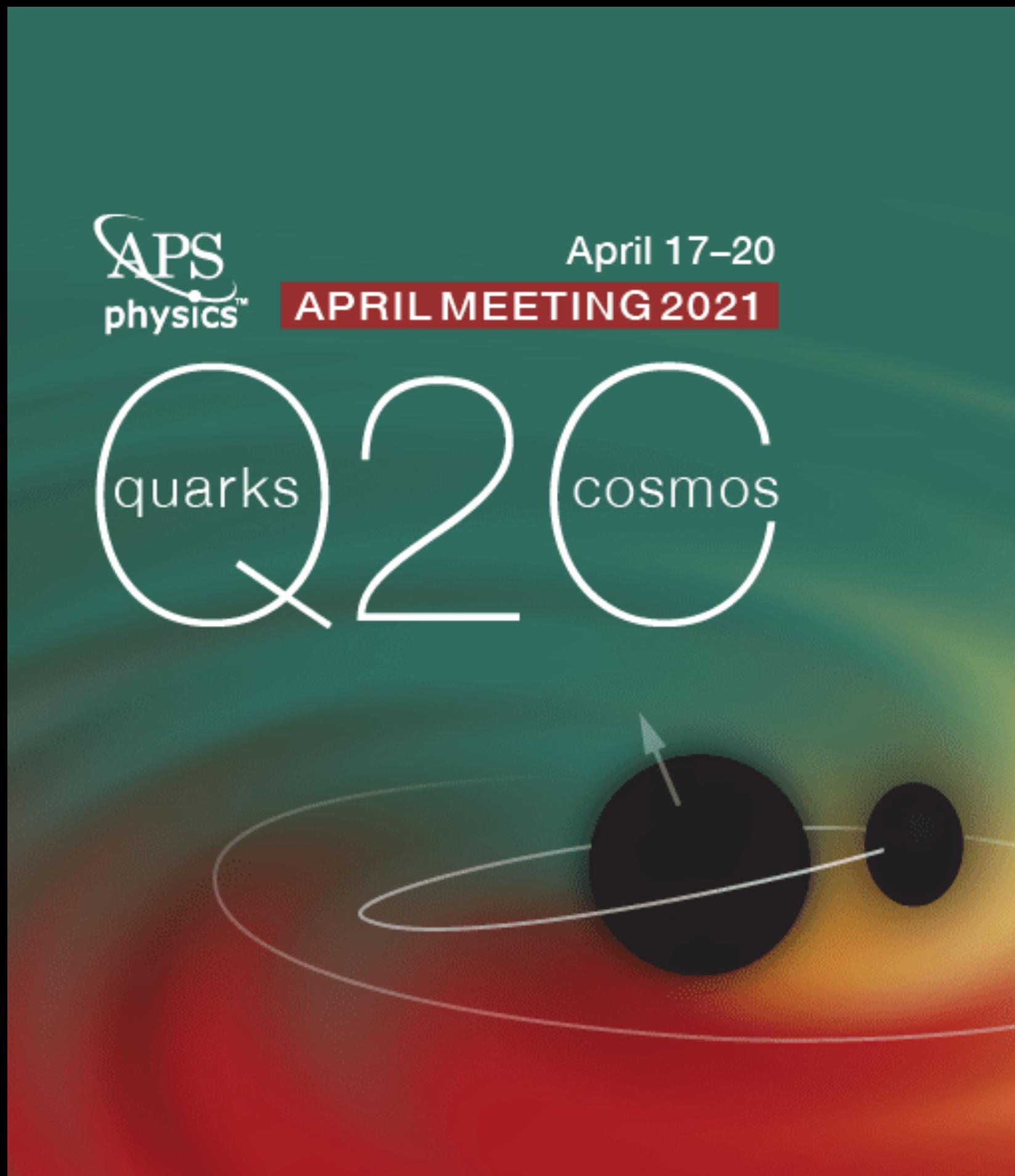
The Case for a Future Muon Collider

Nathaniel Craig

University of California, Santa Barbara

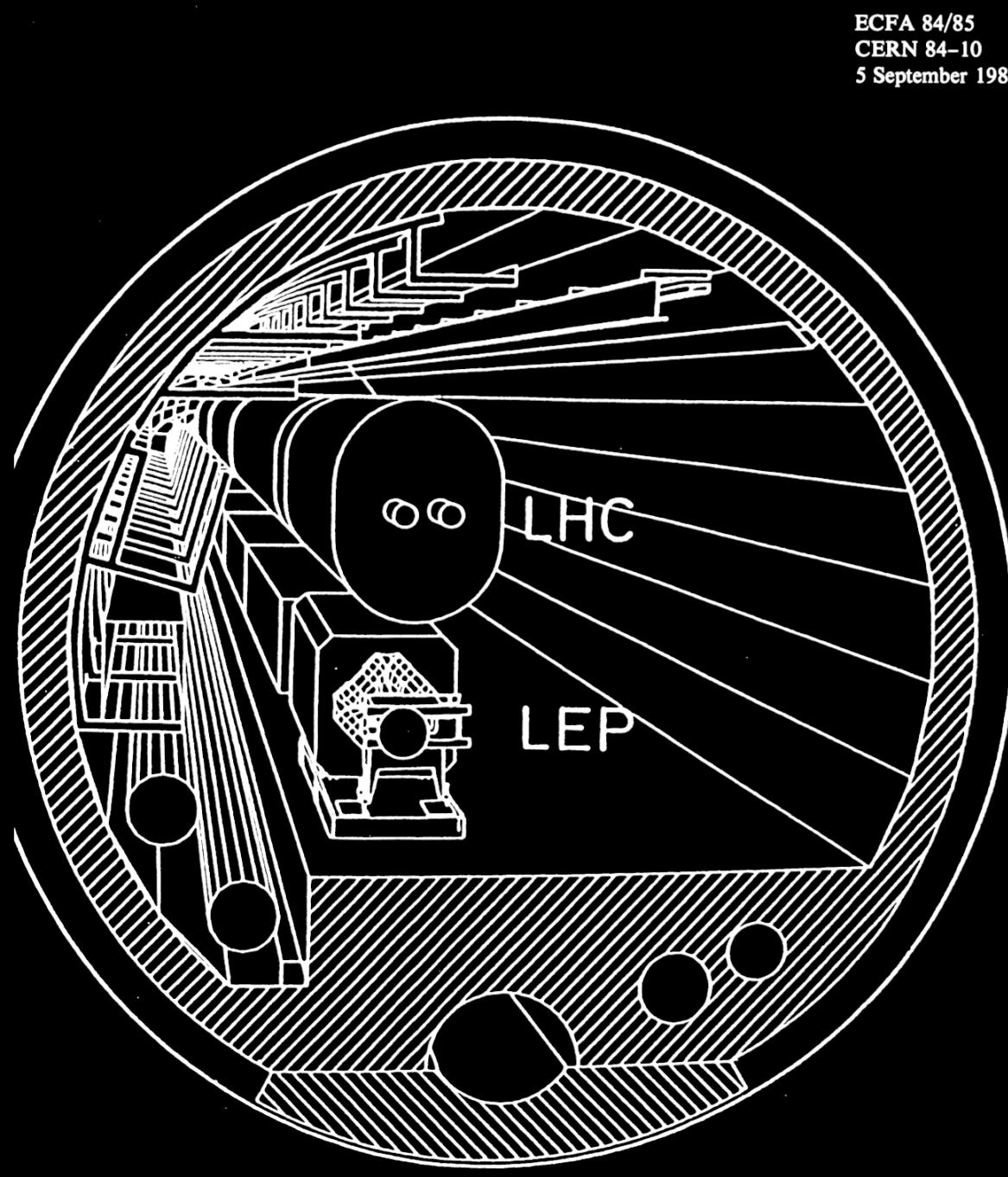
UCSB

Muon Collider Symposium



- **4/17 Session B08:** Muon Collider Symposium I
 - *C. Curatolo*: Beam-induced background
 - *N. Bartosik*: Physics object reconstruction with ILCSoftware
 - *Z. Liu*: WIMPs at muon colliders
 - *L. Sestini*: Jet Reconstruction with BIB
 - *L. Buonincontri*: Triple Higgs coupling
 - *J. Gall*: nuSTORM
- **4/17 Session D14:** Muon Collider Symposium II (talks by *D. Schulte*, *D. Stratakis*, *S. Prestemon*, *D. Bowring*, *X. Wang*, *M. Casarsa*, *E. Gianfelice-Wendt*)
- **4/18 Session H08:** Muon Collider Symposium III (talks by *S. Pagan Griso*, *R. Ruiz*, *H. Weber*, *C. Rogers*, *M. Antonelli*, *K.-P. Xie*, *R. Capdevilla*)
- **4/20 Session Y07:** Muon Collider Symposium IV (talks by *J.P. Delahaye*, *M. Baucé*, *Q. Lu*, *J. Gu*, *L. Vittorio*, *M. Chiesa*, *Y. Ma*, *C. Aime*, *K. Krizka*)

Theory vision circa 1984



LARGE HADRON COLLIDER
IN THE LEP TUNNEL

Vol. I

PROCEEDINGS OF THE ECFA-CERN WORKSHOP

held at Lausanne and Geneva,
21-27 March 1984

Satisfied with these successes, we have now to face deeper questions such as:

what is the origin of mass?

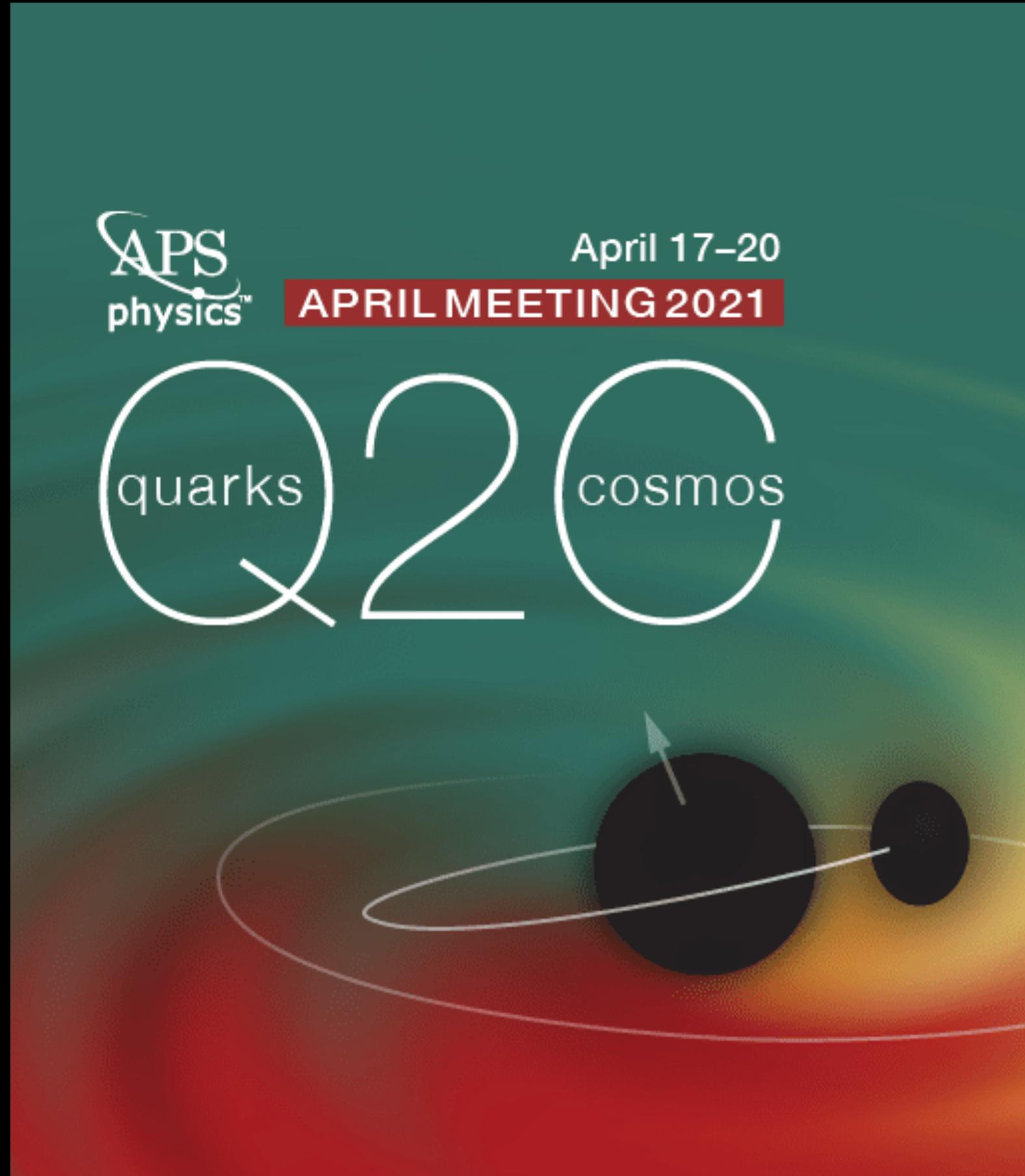
what kind of unification may exist beyond the standard model?

what is the origin of flavour?

is there a deeper reason for gauge symmetry?

We have simply too many a priori plausible hypotheses concerning the nature of symmetry breaking in the standard model. Experimentation in the TeV range at the constituent level is bound to provide most essential clues, and the present successes of the $p\bar{p}$ collider are a very strong encouragement to go to higher energies and to higher luminosities in hadron-hadron collisions.

Theory vision circa 2021

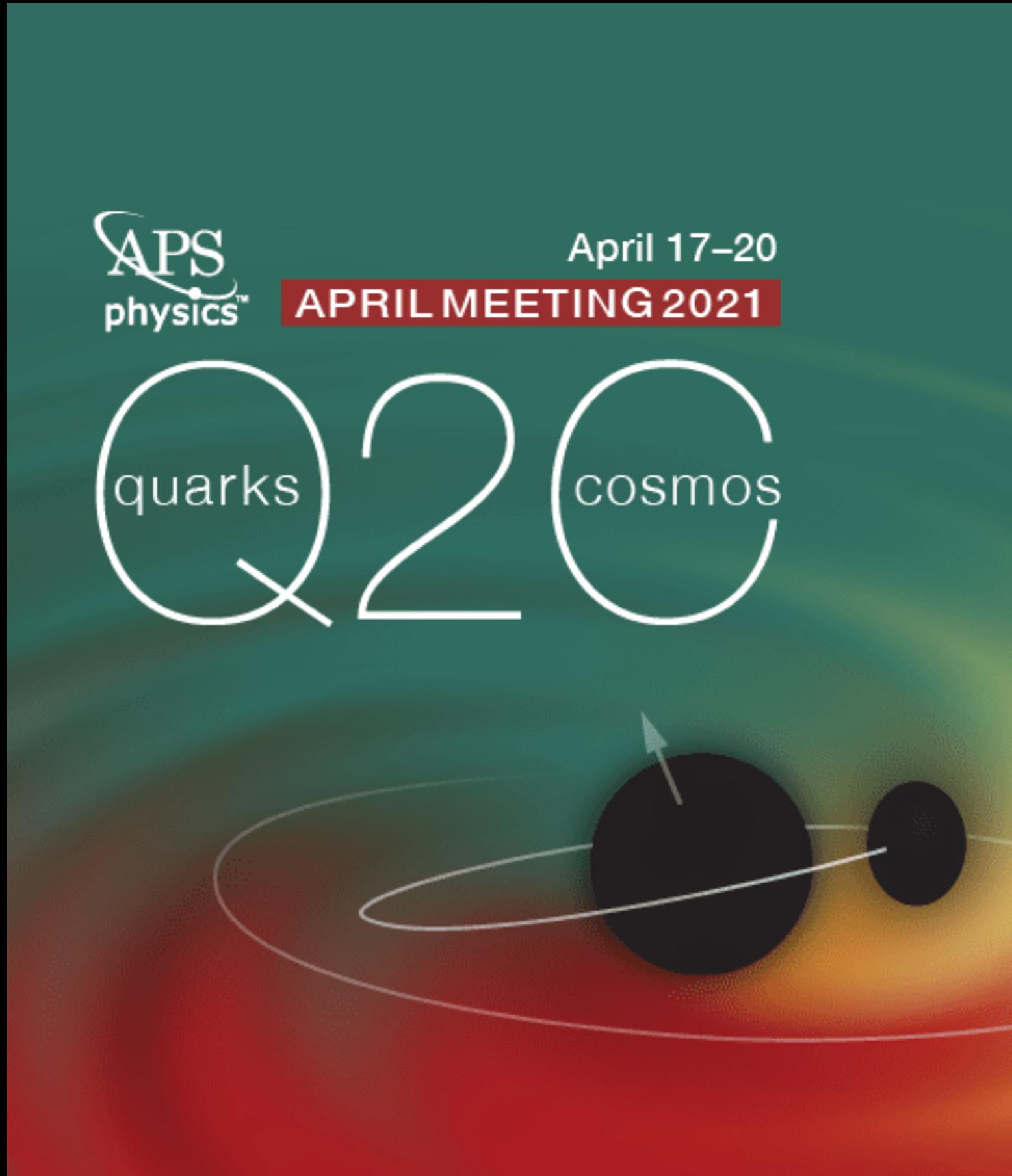


Theory vision circa 2021



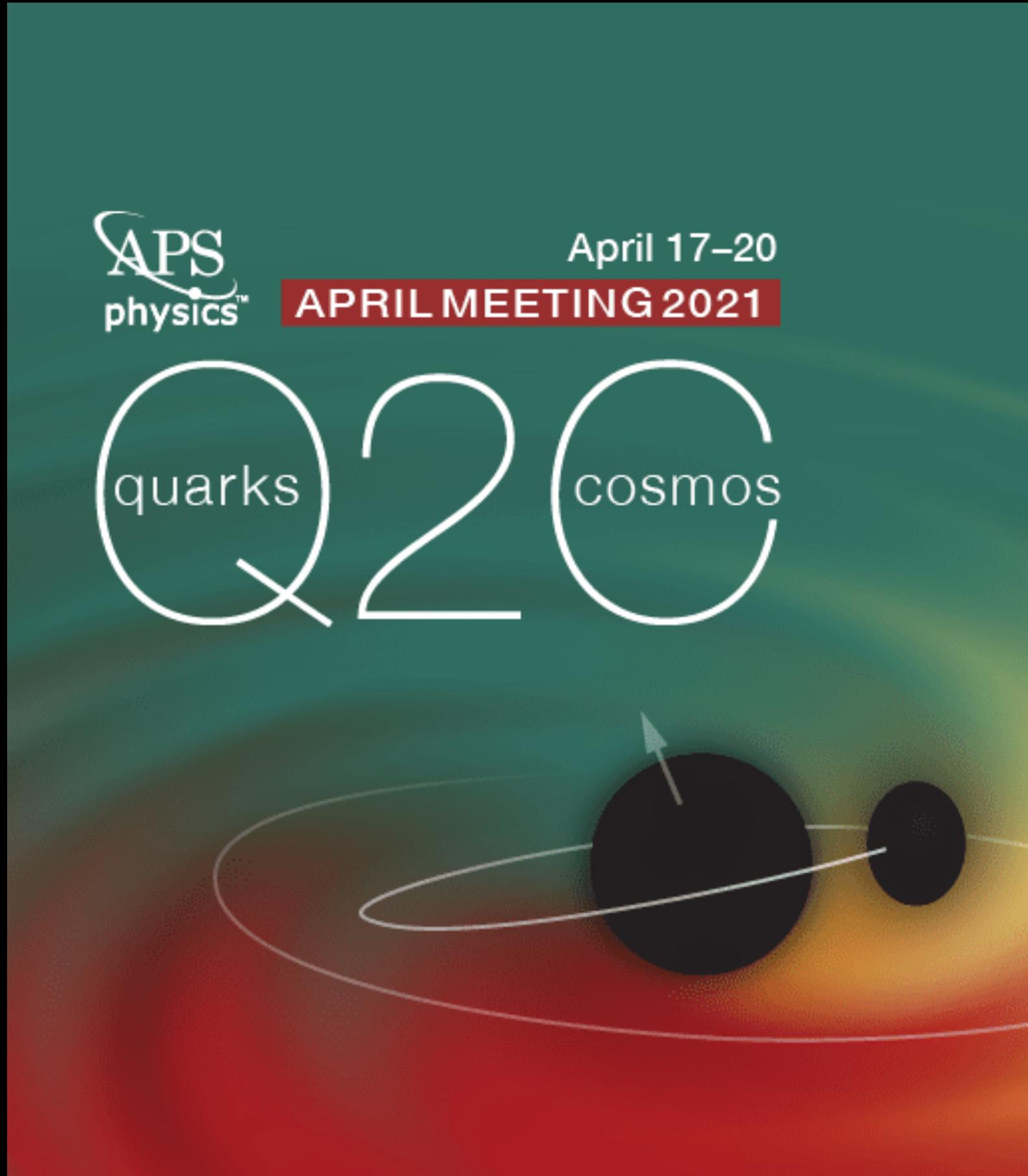
- ✓ What is the origin of mass?
- What kind of unification may exist?
- What is the origin of flavor?
- Is there a deeper reason for gauge symmetry?

Theory vision circa 2021



- ✓ What is the origin of mass?
- What kind of unification may exist?
- What is the origin of flavor?
- Is there a deeper reason for gauge symmetry?
- + What is the nature of dark matter?

Theory vision circa 2021



- ✓ What is the origin of mass?
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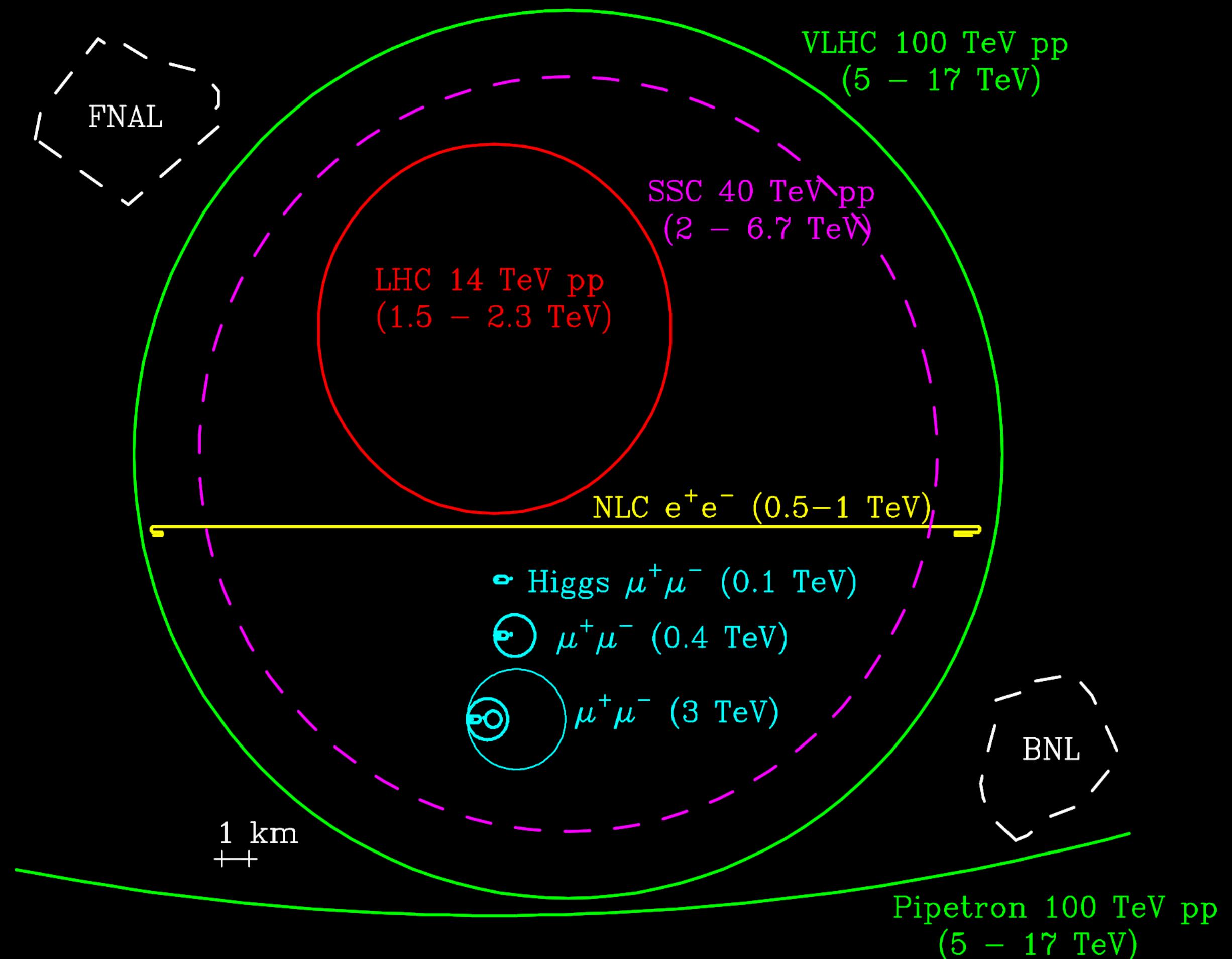
A Higgs! Yet:
Is it the SM Higgs?
Is it the only one?
Why is there EWSB?
What sets the scale?

The path to shorter distances

Conventionally: pursue these questions by probing shorter distances with either **precision** (indirect) or **energy** (direct).

Muon colliders blur this dichotomy.

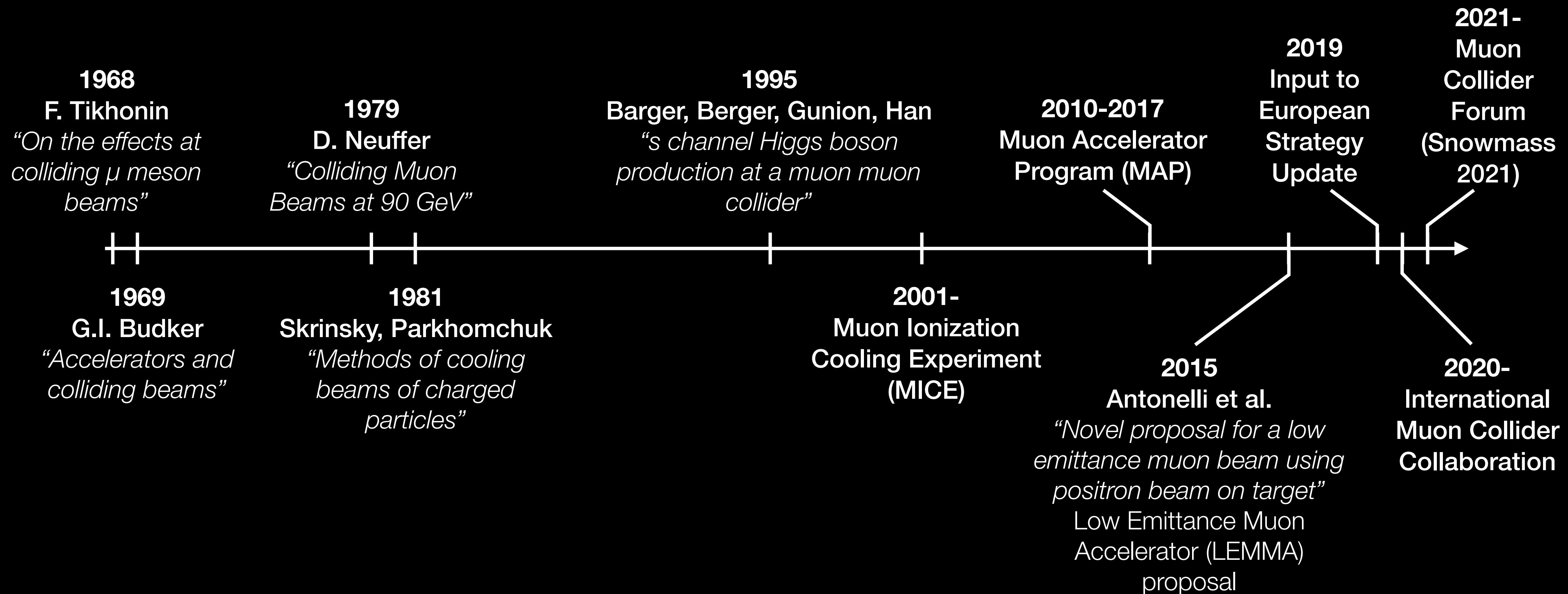
- Colliding elementary particles leverages the **full energy** of the accelerator, with a (relatively) **clean environment**.
- Larger mass of the muon allows a **smaller footprint & higher energies** compared to e^+e^- counterparts.
- **Major challenges:** finite lifetime, cooling

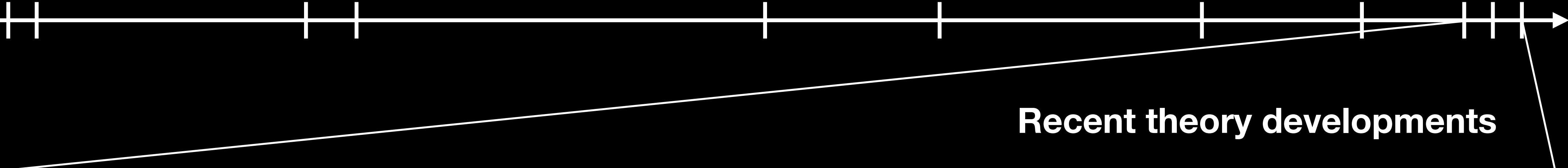


[Ankenbrandt et al. arXiv:physics/9901022]

A brief history of muon colliders

(A wholly incomplete timeline)





Recent theory developments

- **European Strategy Update & Overviews:** [Delahaye et al. 1901.06150; Franceschini & Greco 2104.05770]
- **PDFs of the muon:** [Han, Ma, Xie 2007.14300, 2103.09844]
- **New scalars & other BSM particles:** [Buttazzo, Redigolo, Sala, Tesi 1807.04743; Costantini et al. 2005.10289; Bandyopadhyay & Costantini 2010.02597; Kalinowski, Robens, Sokolowska, Zarnecki 2012.14818; Han, Li, Su, Su, Wu 2102.08386; Liu, Xi 2101.10469, ...]
- **Dark matter:** [Han, Liu, Wang, Wang 2009.11287; Capdevilla, Meloni, Simoniella, Zurita 2102.11292, ...]
- **Higgs self-couplings & electroweak couplings:** [Chiesa, Maltoni, Mantani, Mele, Piccinini, Zhao 2003.13628; Han, Liu, Low, Wang 2008.12204, ...]
- **Indirect effects / irrelevant operators:** [Di Luzio, Groeber, Panico 1810.10993; Buttazzo, Franceschini, Wulzer 2012.11555, ...]
- **Anomalies (muon g-2, B flavor):** [Capdevilla, Curtin, Kahn, Krnjaic 2006.16277, 2101.10334; Buttazzo, Paradisi 2012.02769; Chen, Wang, Yao 2102.05619; Yin, Yamaguchi 2012.03928; Huang, Queiroz, Rodejohann 2101.04956; Huang, Jana, Queiroz, Rodejohann 2103.01617; Asadi, Capdevilla, Cesarotti, Homiller 2104.05720]

The Muon Smasher's Guide

[arXiv: 2103.14043]

Hind Al Ali¹, Nima Arkani-Hamed², Ian Banta¹, Sean Benevides¹, Dario Buttazzo³, Tianji Cai¹, Junyi Cheng¹, Timothy Cohen⁴, Nathaniel Craig¹, Majid Ekhterachian⁵, JiJi Fan⁶, Matthew Forslund⁷, Isabel Garcia Garcia⁸, Samuel Homiller⁹, Seth Koren¹⁰, Giacomo Koszegi¹, Zhen Liu^{5,11}, Qianshu Lu⁹, Kun-Feng Lyu¹², Alberto Mariotti¹³, Amara McCune¹, Patrick Meade⁷, Isobel Ojalvo¹⁴, Umut Oktem¹, Diego Redigolo^{15,16}, Matthew Reece⁹, Filippo Sala¹⁷, Raman Sundrum⁵, Dave Sutherland¹⁸, Andrea Tesi^{16,19}, Timothy Trott¹, Chris Tully¹⁴, Lian-Tao Wang¹⁰, and Menghang Wang¹

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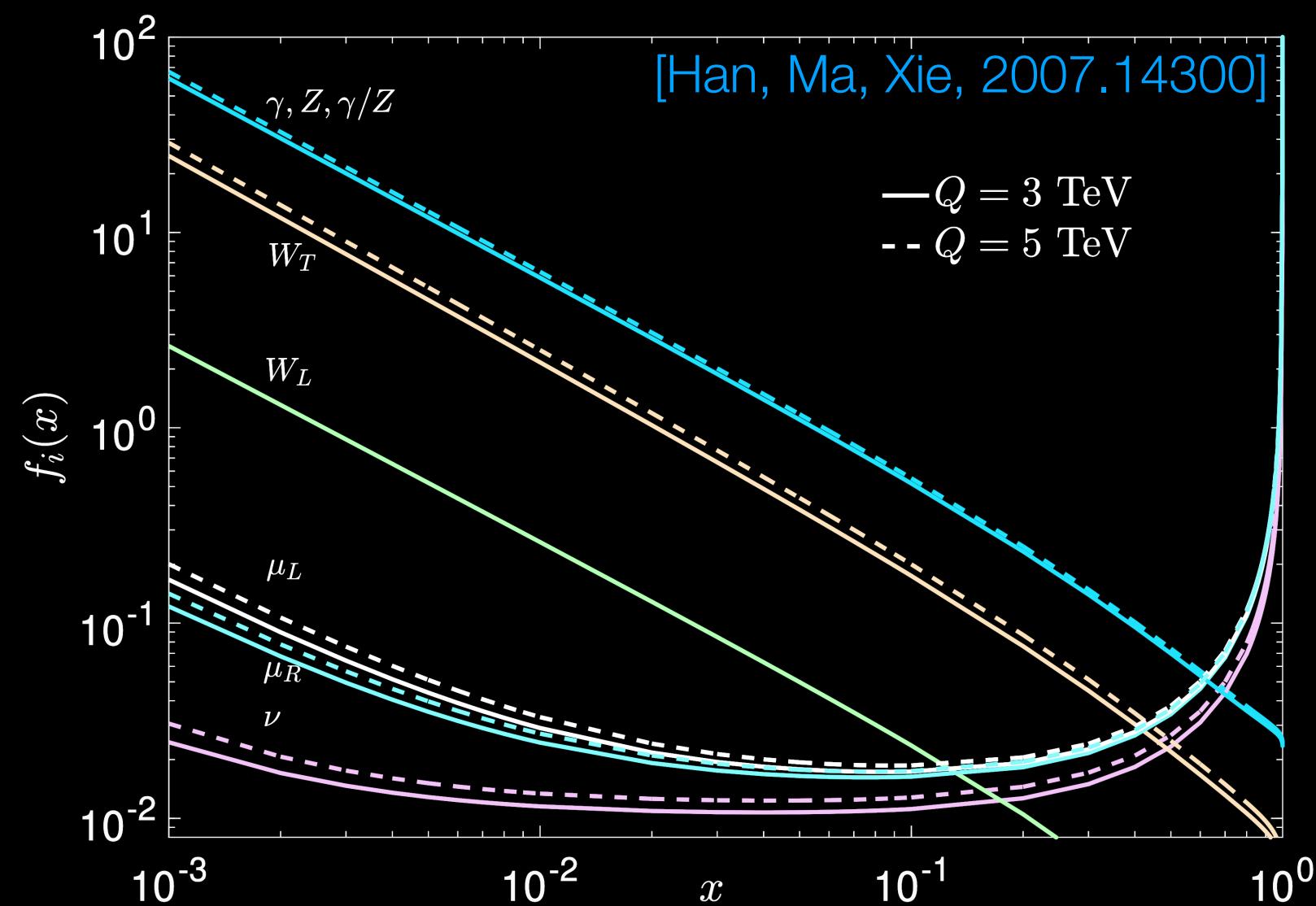
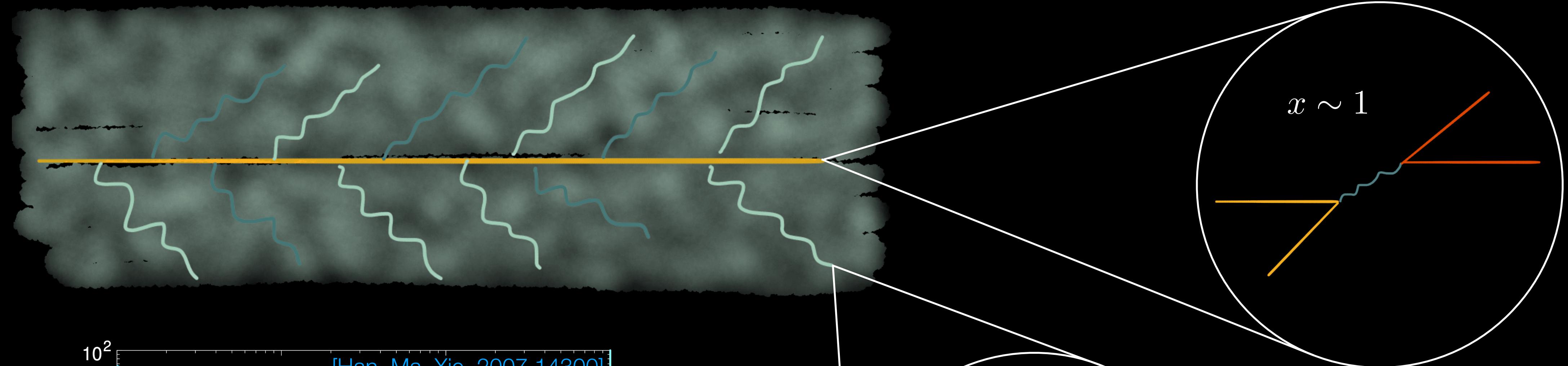
Coarse-grained approach to phenomenology: interested in rates, simple parton-level analyses, setting aside beam-induced background & reconstruction issues.

Broad goal: to figure out what energies & luminosities might provide a comprehensive physics case, bring new targets into focus.

Various luminosity assumptions & energies:

\sqrt{s} [TeV]	1	3	6	10	14	30	50	100
$\mathcal{L}_{\text{int}}^{\text{opt}}$ [ab $^{-1}$]	0.2	1	4	10	20	90	250	1000
$\mathcal{L}_{\text{int}}^{\text{con}}$ [ab $^{-1}$]	0.2	1	4	10	10	10	10	10

The Quantum Muon

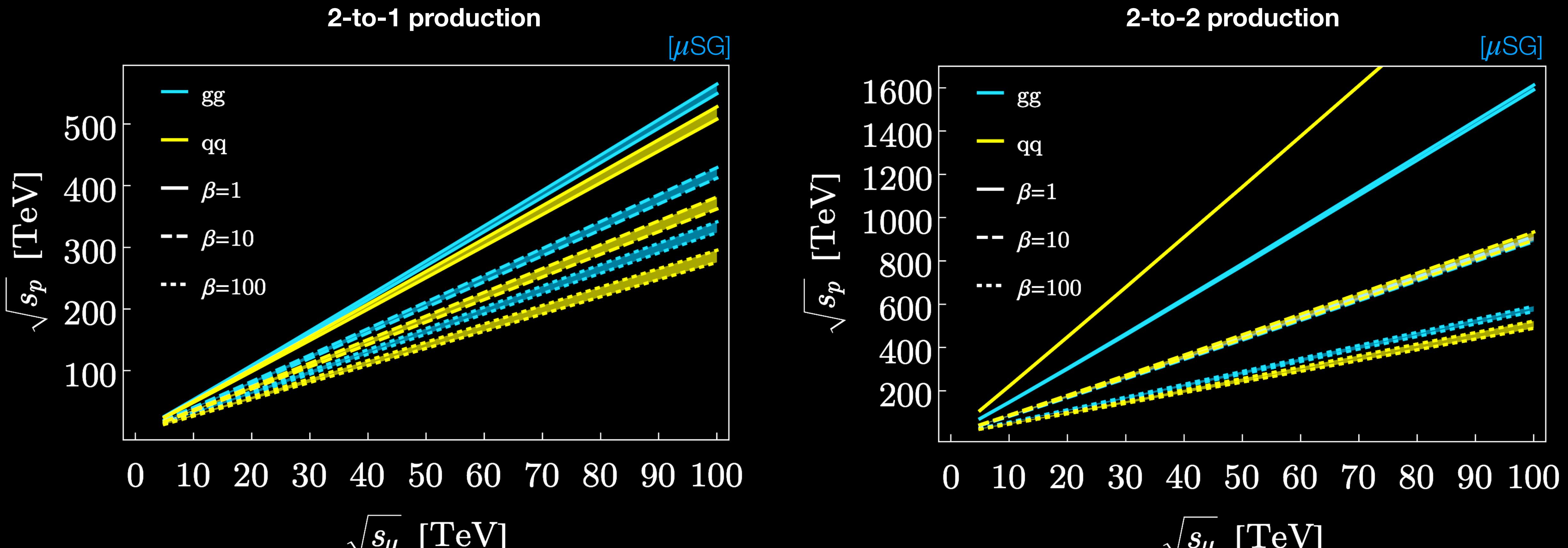


Muon annihilation
deploys the entire
energy of the collider

Vector boson fusion
leverages the muon's
virtual boson content

Muon annihilation & pp equivalents

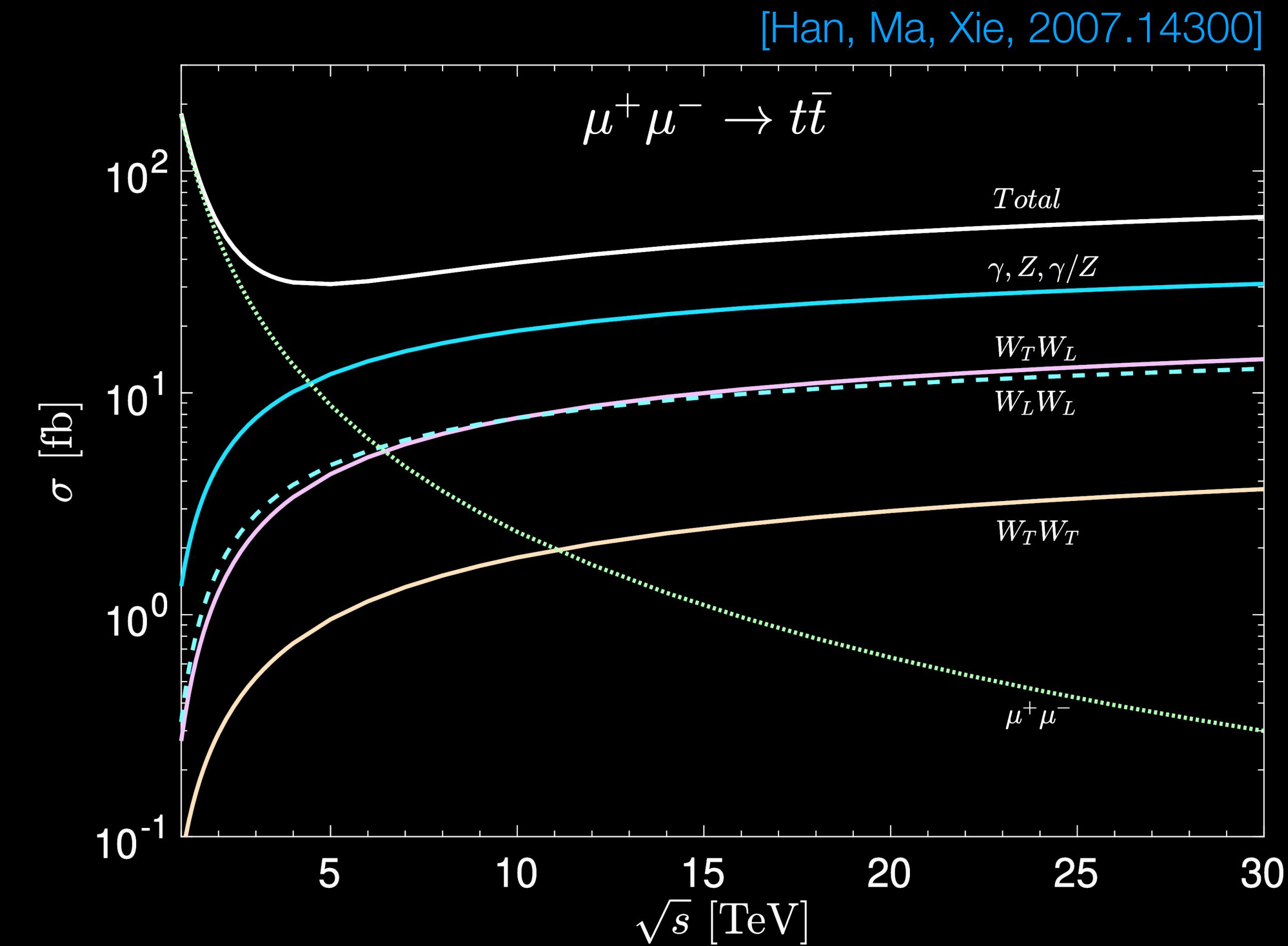
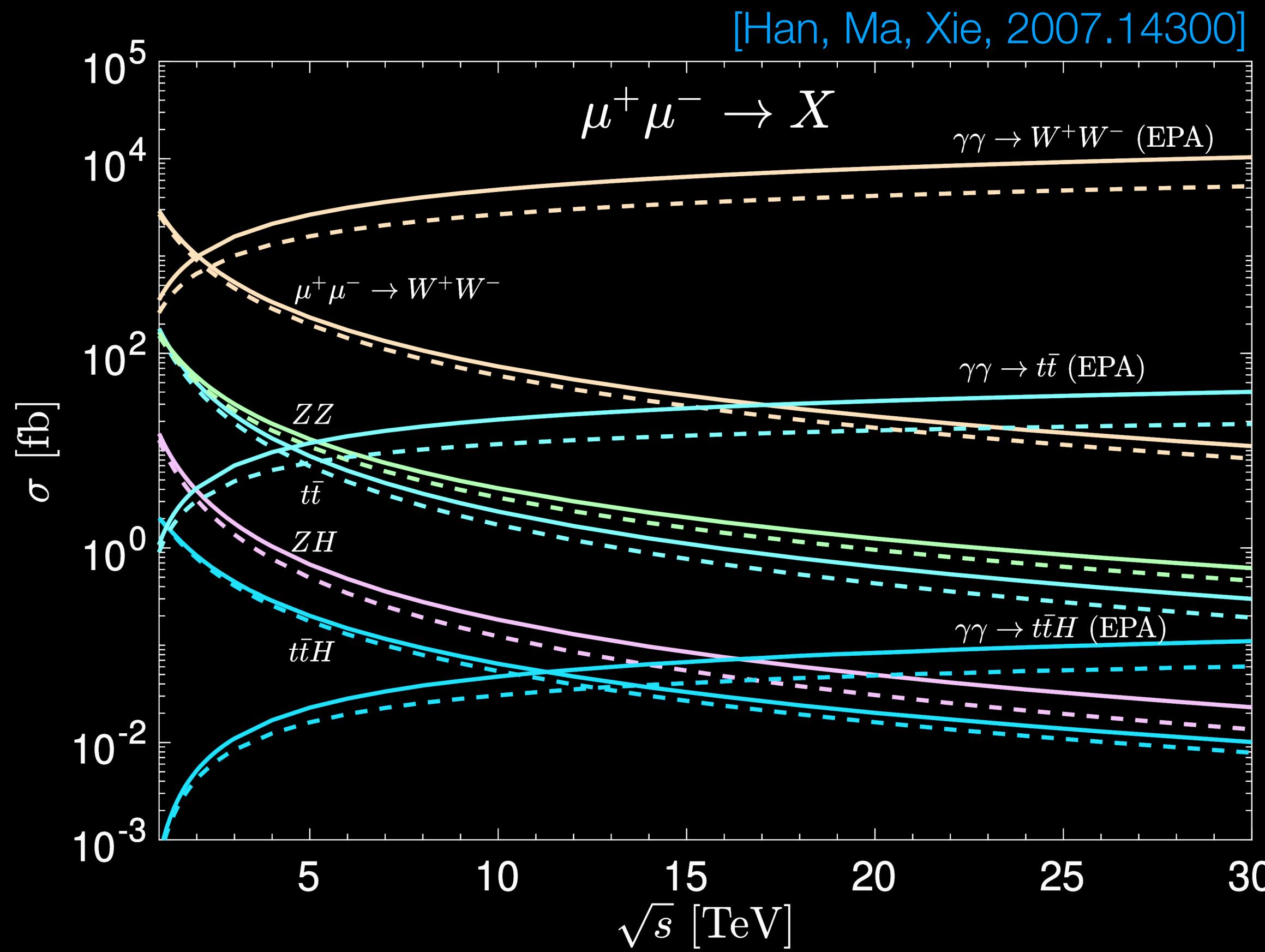
In the spirit of [Delahaye et al. 1901.06150, Costantini et al. 2005.10289]



(Bands are NNPDF3.0 LO vs. CT18NNLO)

Comparison favorable to MC in that $\hat{s} = s_\mu = M^2$ for 2-to-1 and $\hat{s} = s_\mu = 4M^2$ for 2-to-2

VBF: μ Cs as Vector Factories



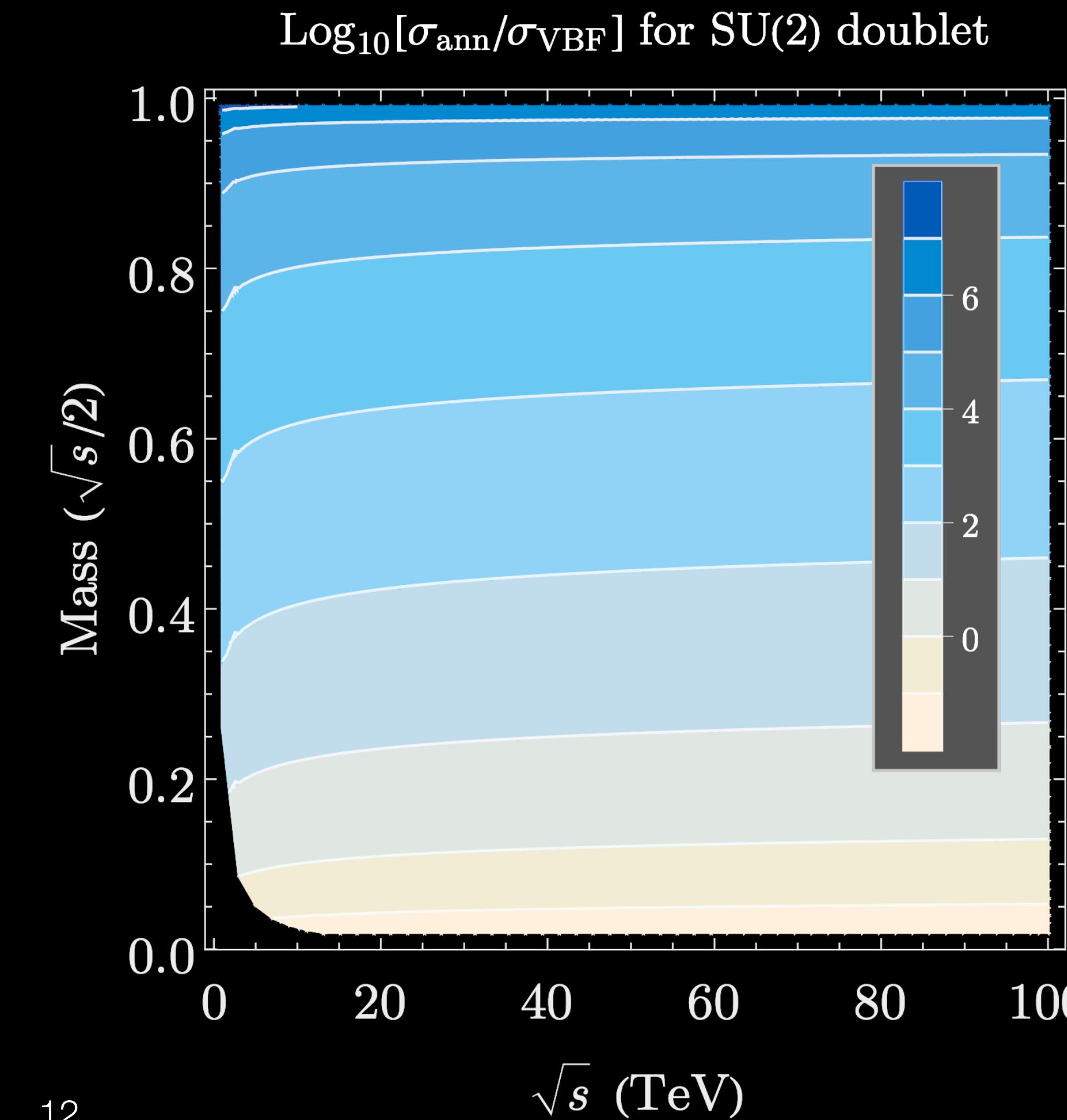
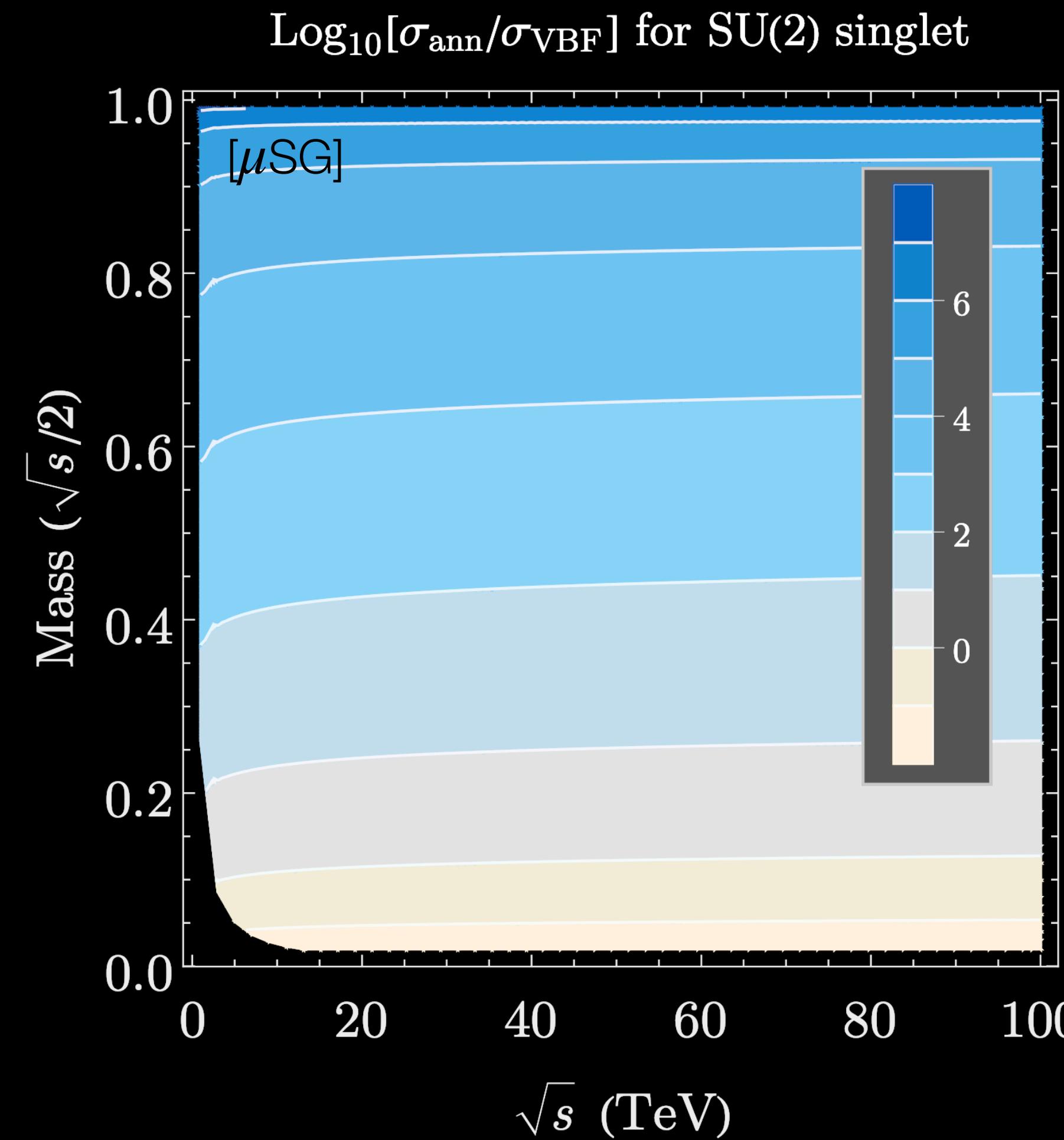
*VBF dominates well above threshold
due to logarithmic growth with E_{CM}*

*Longitudinal polarizations play a key role,
making an extraordinary laboratory for EWSB*

Two channels for new physics

Combination of annihilation and VBF offers kinematic reach and considerable rate

c.f. [Costantini et al. 2005.10289]



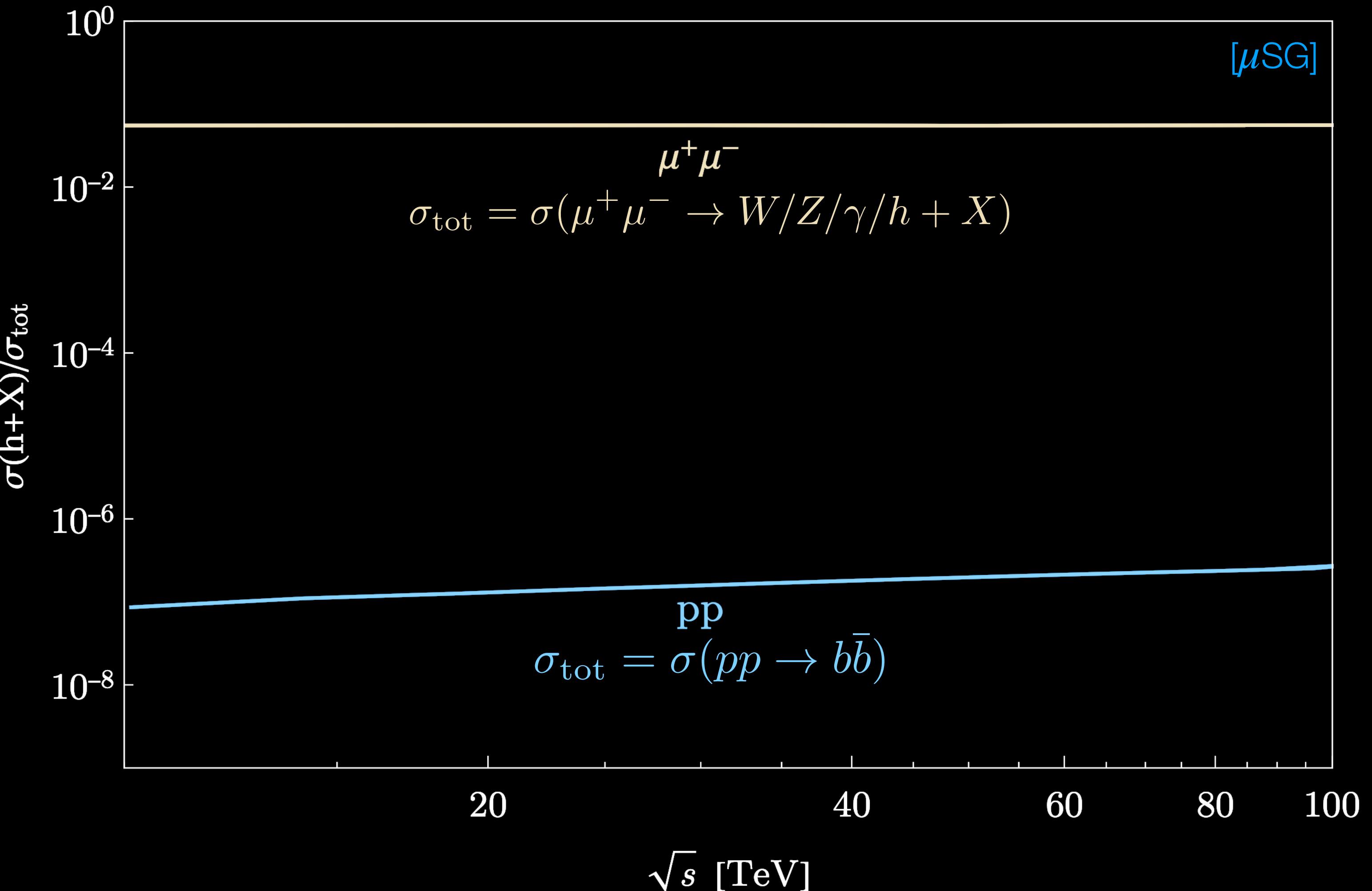
What is the origin of mass?

A Higgs! Yet:
Is it the SM Higgs?
Is it the only one?
Why is there EWSB?
What sets the scale?

The Higgs itself is key.

Any deviation in its properties from SM predictions is a telltale sign of new physics.

S/B favorable at a μ C.



Precision probes of the Higgs

κ fit in “ κ -0” scenario (no invisible/untagged BR, no HL-LHC combination)

For illustration only: Muon collider projections for $\sqrt{s} = 10$ TeV, 10/ab using fast sim, DELPHES μ C detector card, minimal cuts/tagging. No physics backgrounds or BIB, though latter plausibly under control [Bartosik et al. 2001.04431]

κ -0 fit	HL-LHC	LHeC	HE-LHC			ILC			CLIC			CEPC	FCC-ee	FCC-ee/ eh/hh	$\mu^+\mu^-$ 10000
			S2	S2'	250	500	1000	380	1500	3000	240				
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14	0.06
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12	0.23
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49	0.15
κ_γ [%]	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98*	5.0	2.2	3.7	4.7	3.9	0.29	0.64
$\kappa_{Z\gamma}$ [%]	10.	—	5.7	3.8	99*	86*	85*	120*	15	6.9	8.2	81*	75*	0.69	1.0
κ_c [%]	—	4.1	—	—	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95	0.89
κ_t [%]	3.3	—	2.8	1.7	—	6.9	1.6	—	—	2.7	—	—	—	1.0	7.49
κ_b [%]	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43	0.16
κ_μ [%]	4.6	—	2.5	1.7	15	9.4	6.2	320*	13	5.8	8.9	10	8.9	0.41	1.95
κ_τ [%]	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44	0.27

Other entries: [de Blas et al. 1905.03764]. Also: hhh~5.6% [Han, Liu, Low, Wang 2008.12204]

Energetic probes of the Higgs

High-energy measurements equally powerful [Buttazzo, Franceschini, Wulzer, 2012.11555]

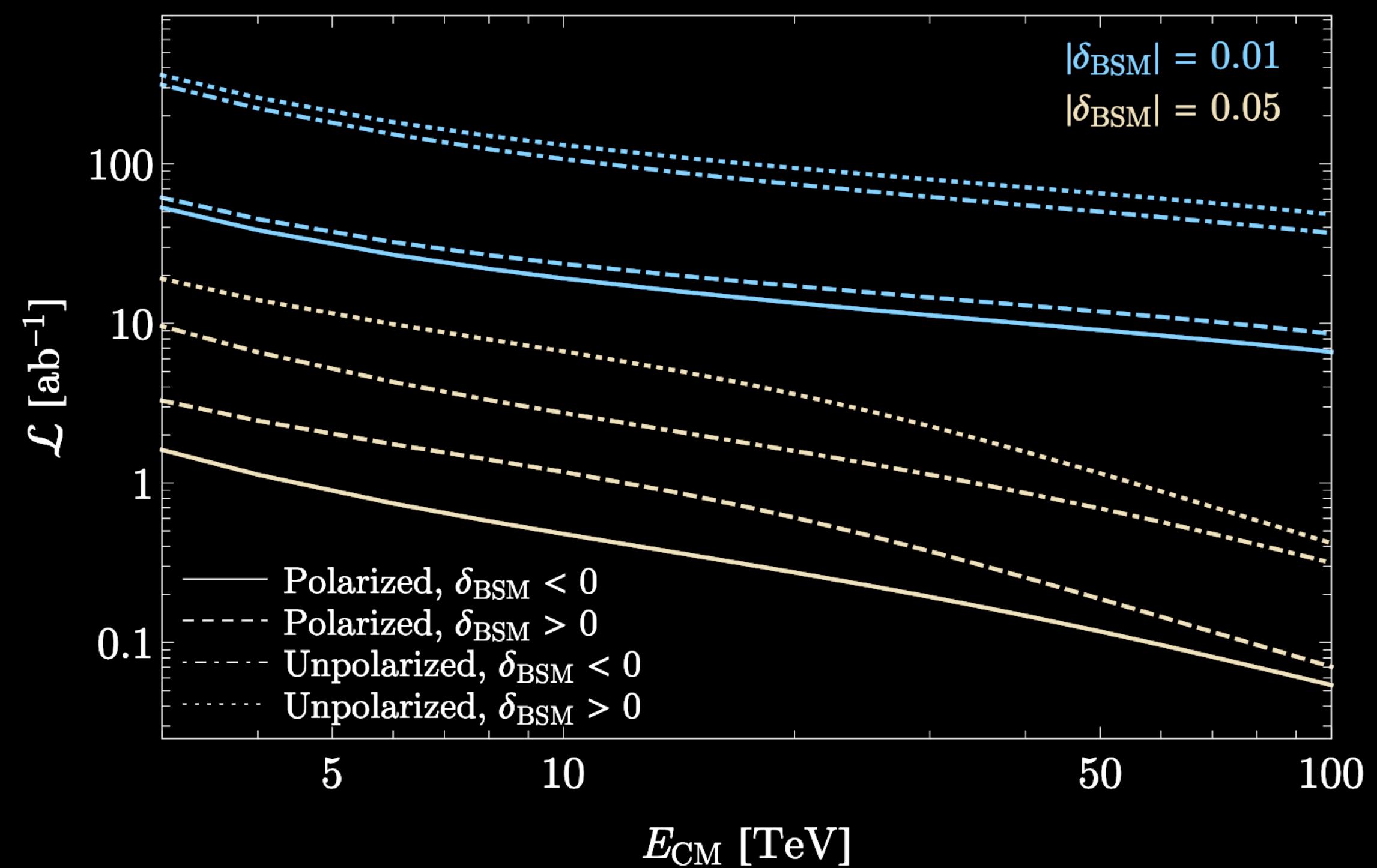
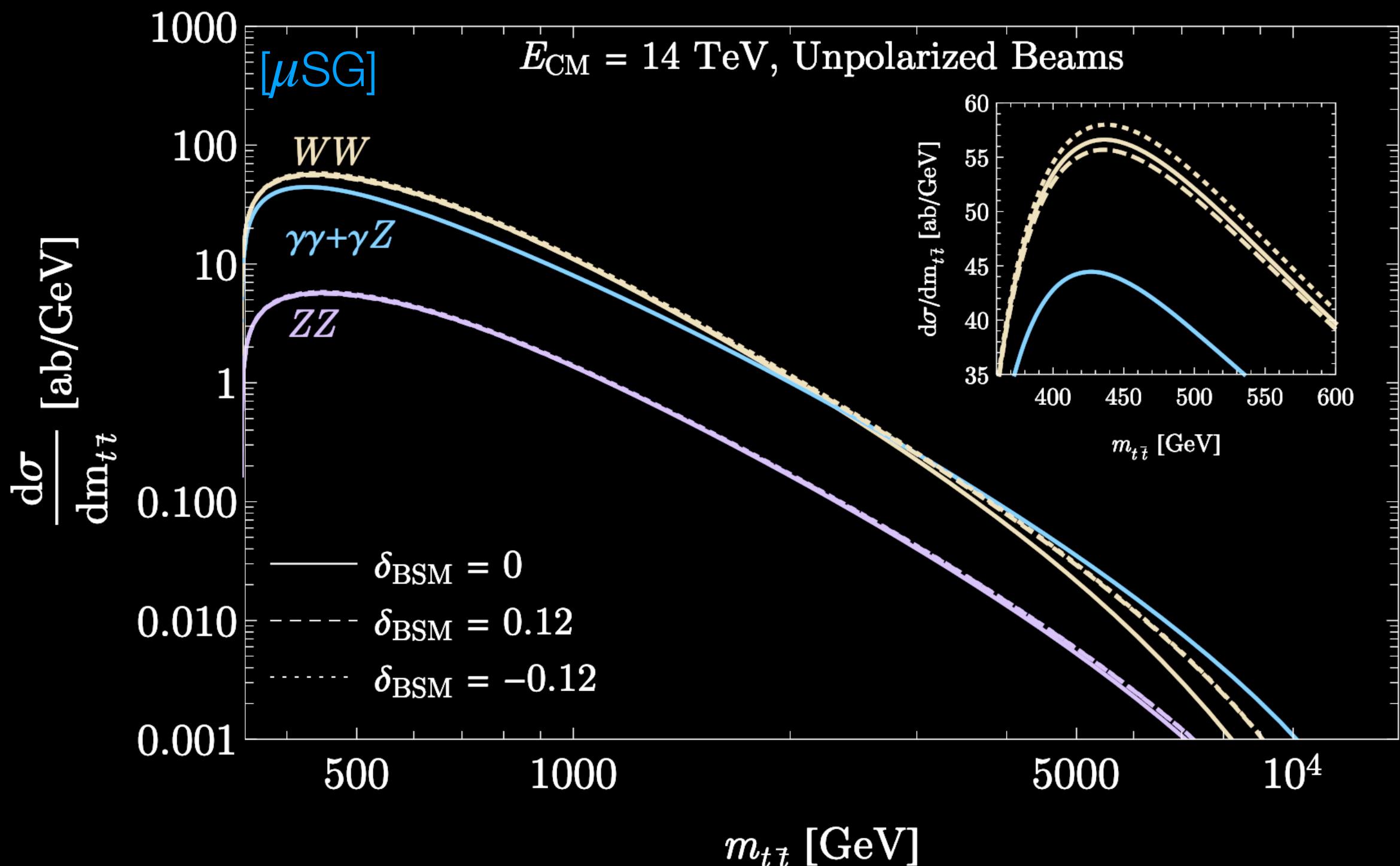
For example: measuring Higgs-top coupling in high-energy $t\bar{t}$

Expect to remain an interesting target after HL-LHC/Higgs factory ($|\delta_{\text{BSM}}| < 0.06$)

$$y_t \rightarrow y_t(1 + \delta_{\text{BSM}})$$

$$\mathcal{M}(W_L^+ W_L^- \rightarrow t\bar{t}) \approx -\frac{m_t}{v^2} \delta_{\text{BSM}} \sqrt{\hat{s}}$$

$$\sqrt{\hat{s}} \gg m_t$$



Is our Higgs the only one?

Many possible extensions of the scalar sector...

For illustration: a Standard Model singlet mixing with the Higgs.

$$h = h^0 \cos \gamma + S \sin \gamma$$

$$\phi = S \cos \gamma - h^0 \sin \gamma$$

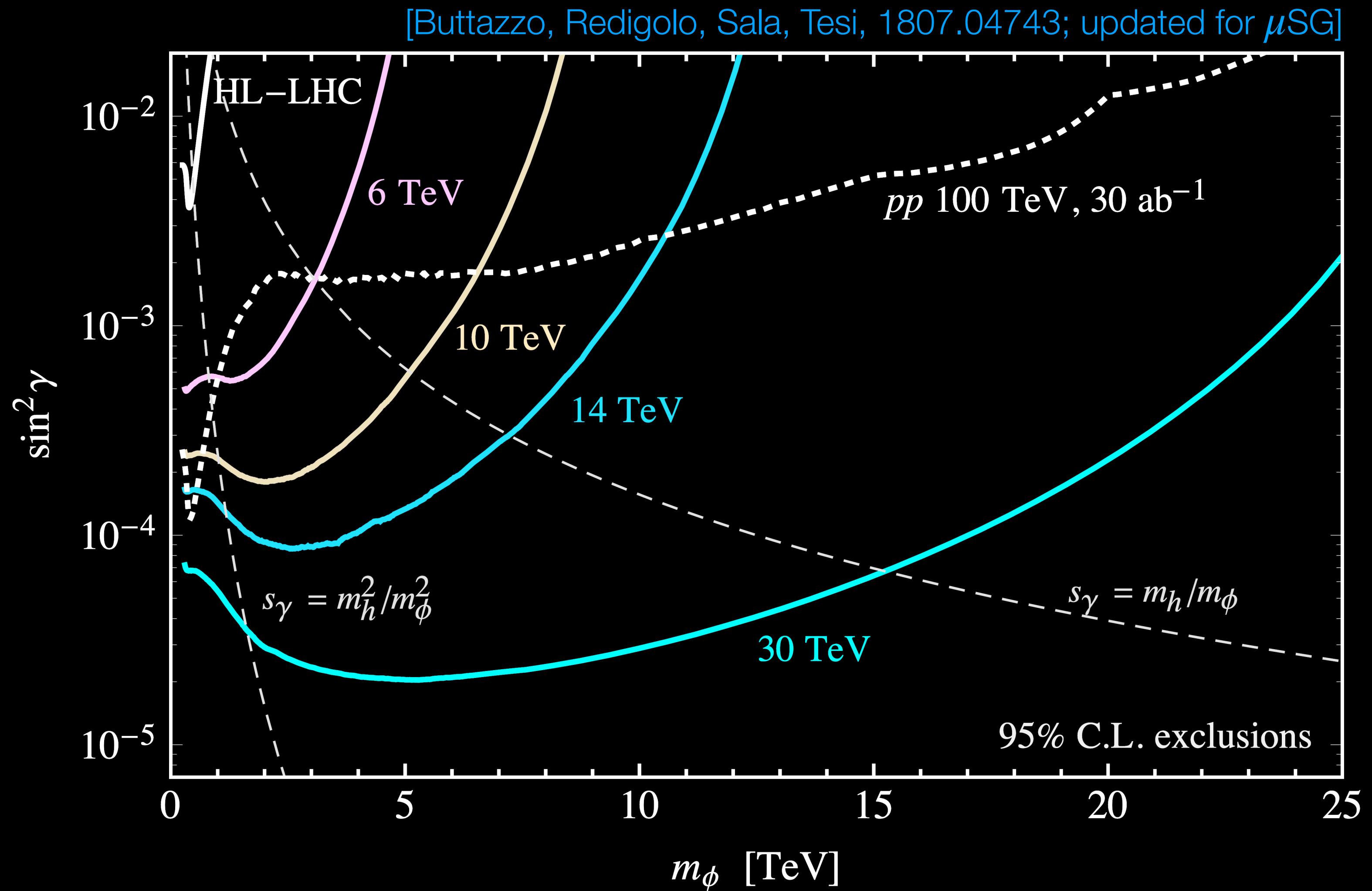
Production:

$$\sigma_\phi = \sin^2 \gamma \cdot \sigma_h(m_\phi)$$

Decay:

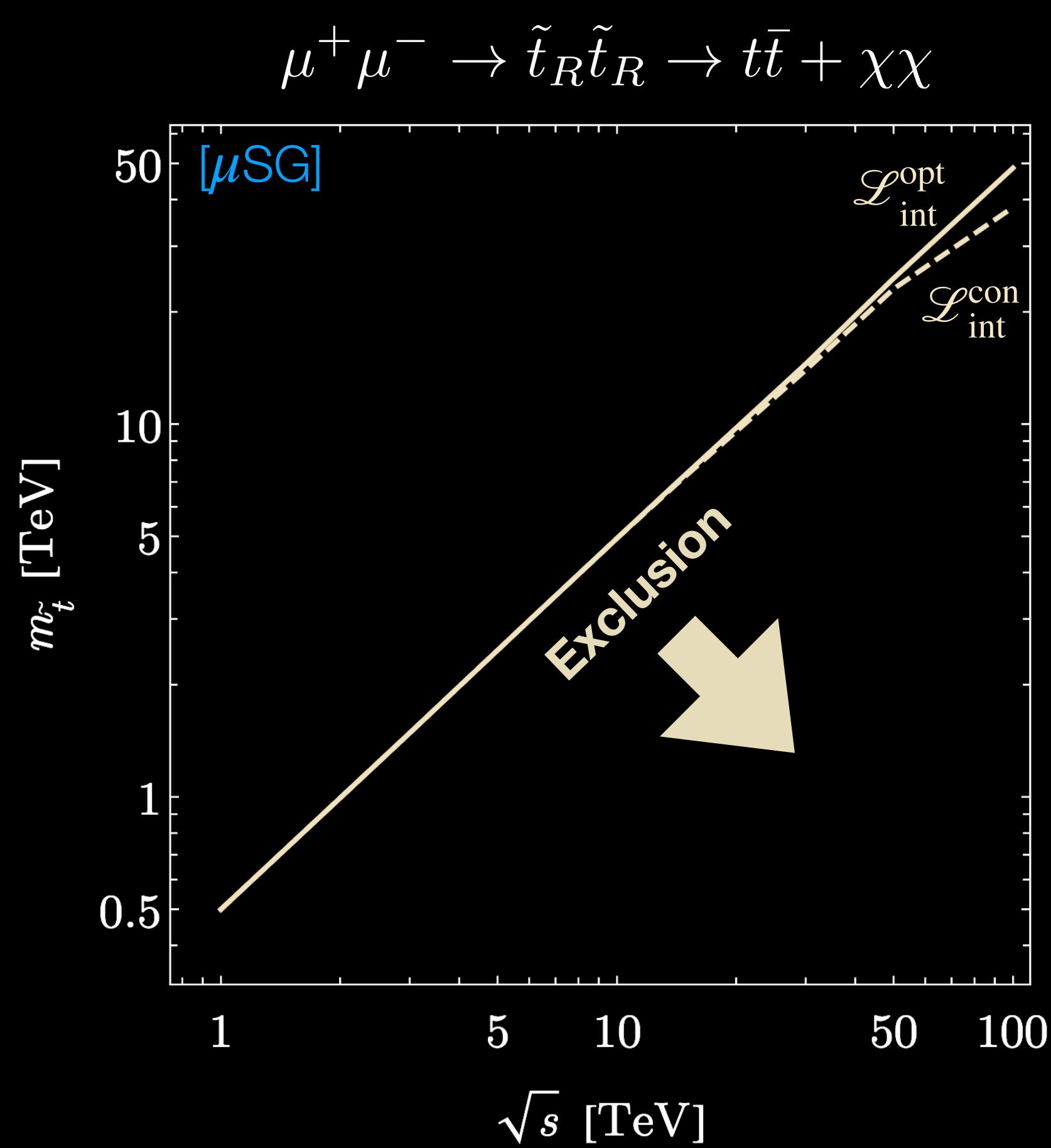
$$\text{BR}_{\phi \rightarrow f\bar{f}, VV} = \text{BR}_{h \rightarrow f\bar{f}, VV} (1 - \text{BR}_{\phi \rightarrow hh})$$

$$\text{BR}_{\phi \rightarrow hh} \sim 25\%$$

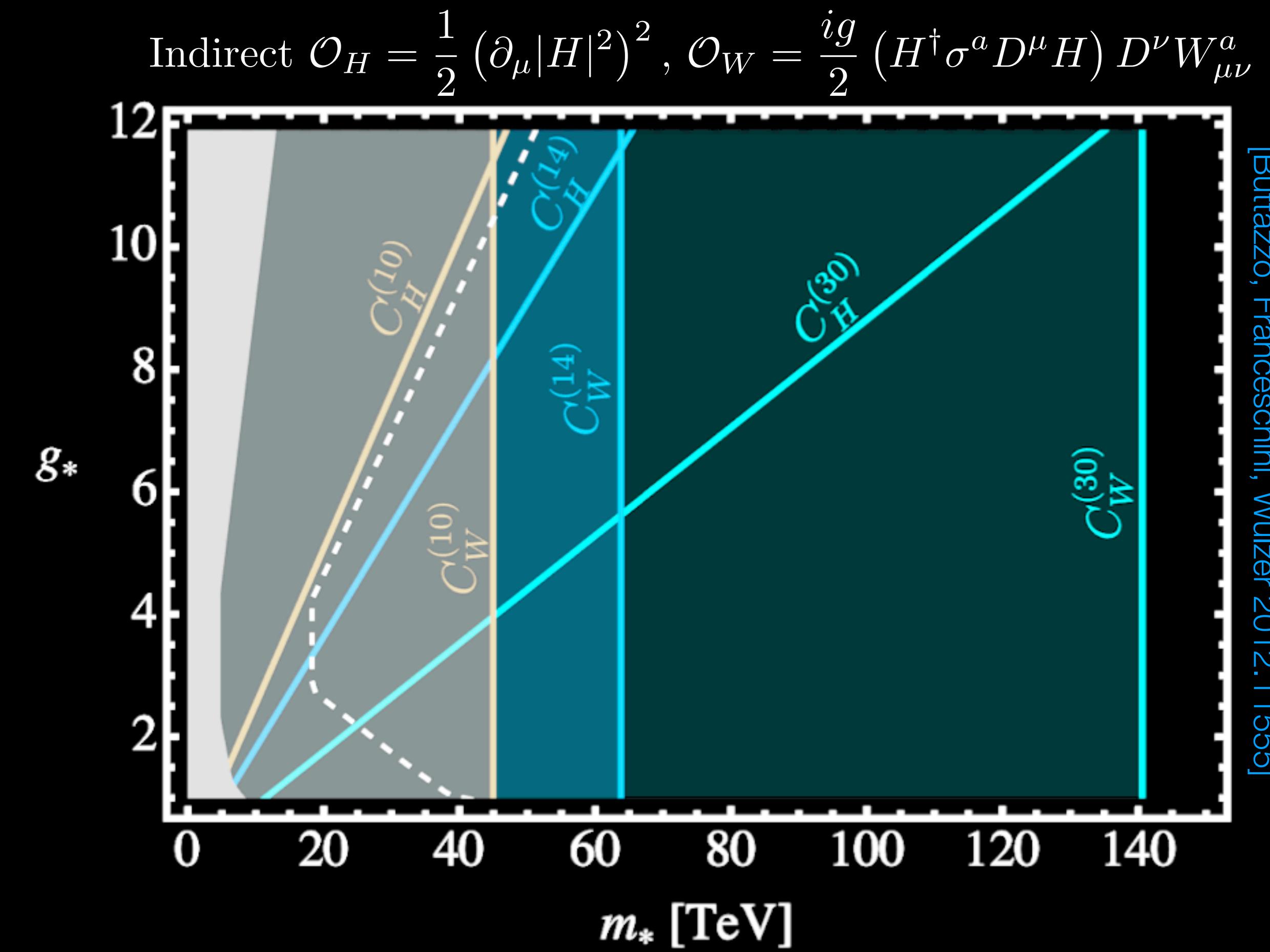


Why EWSB? What sets the scale?

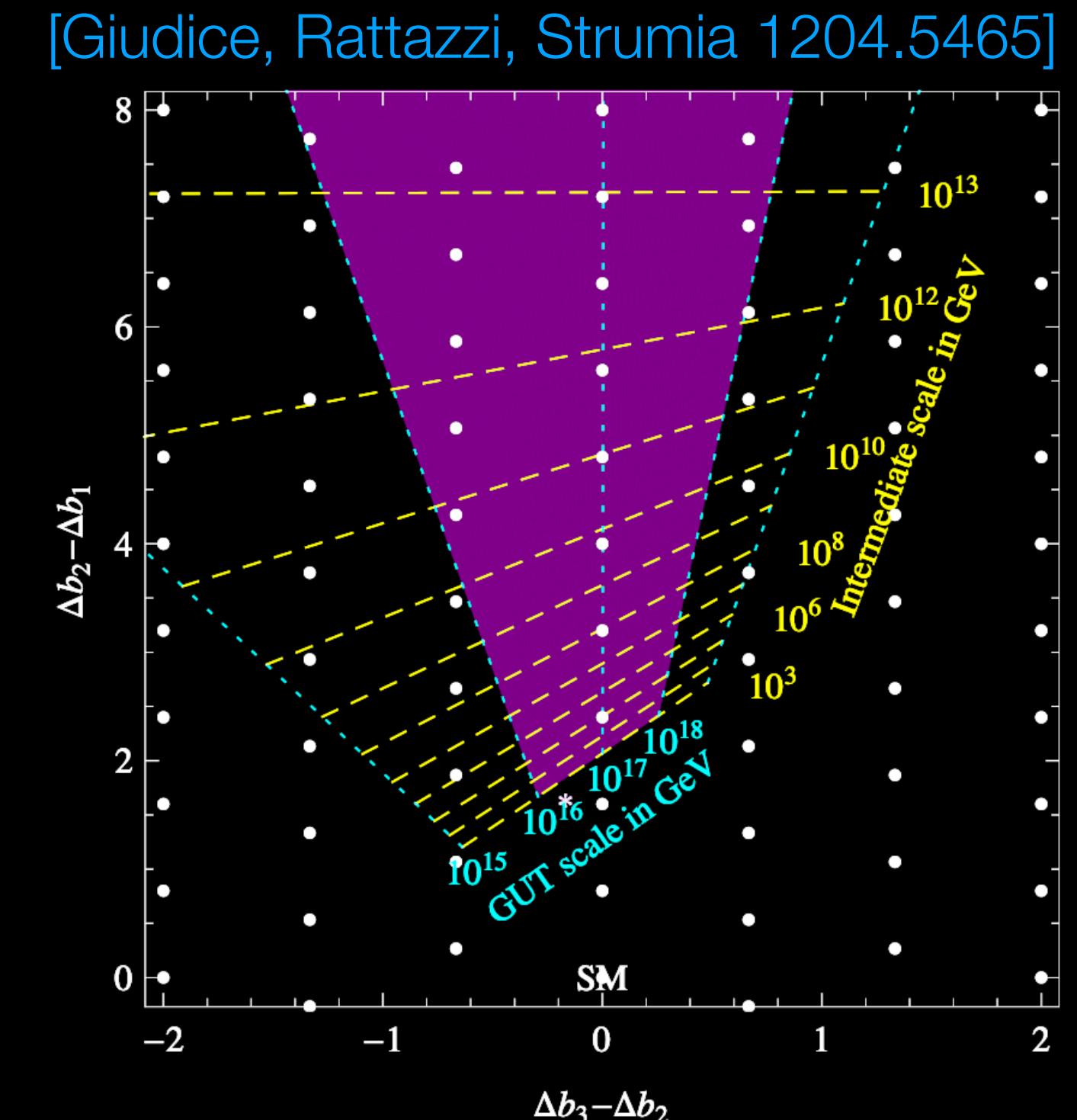
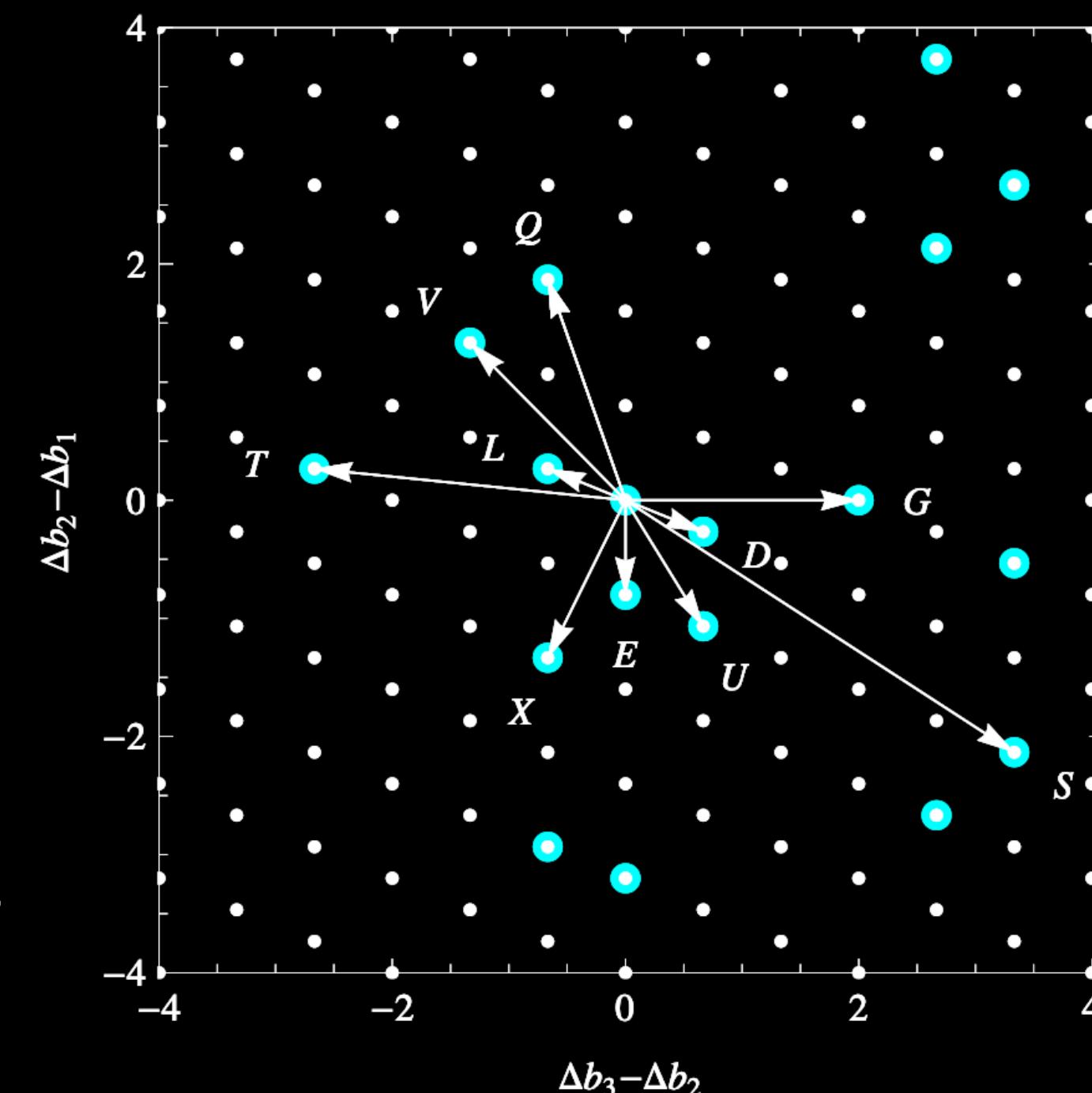
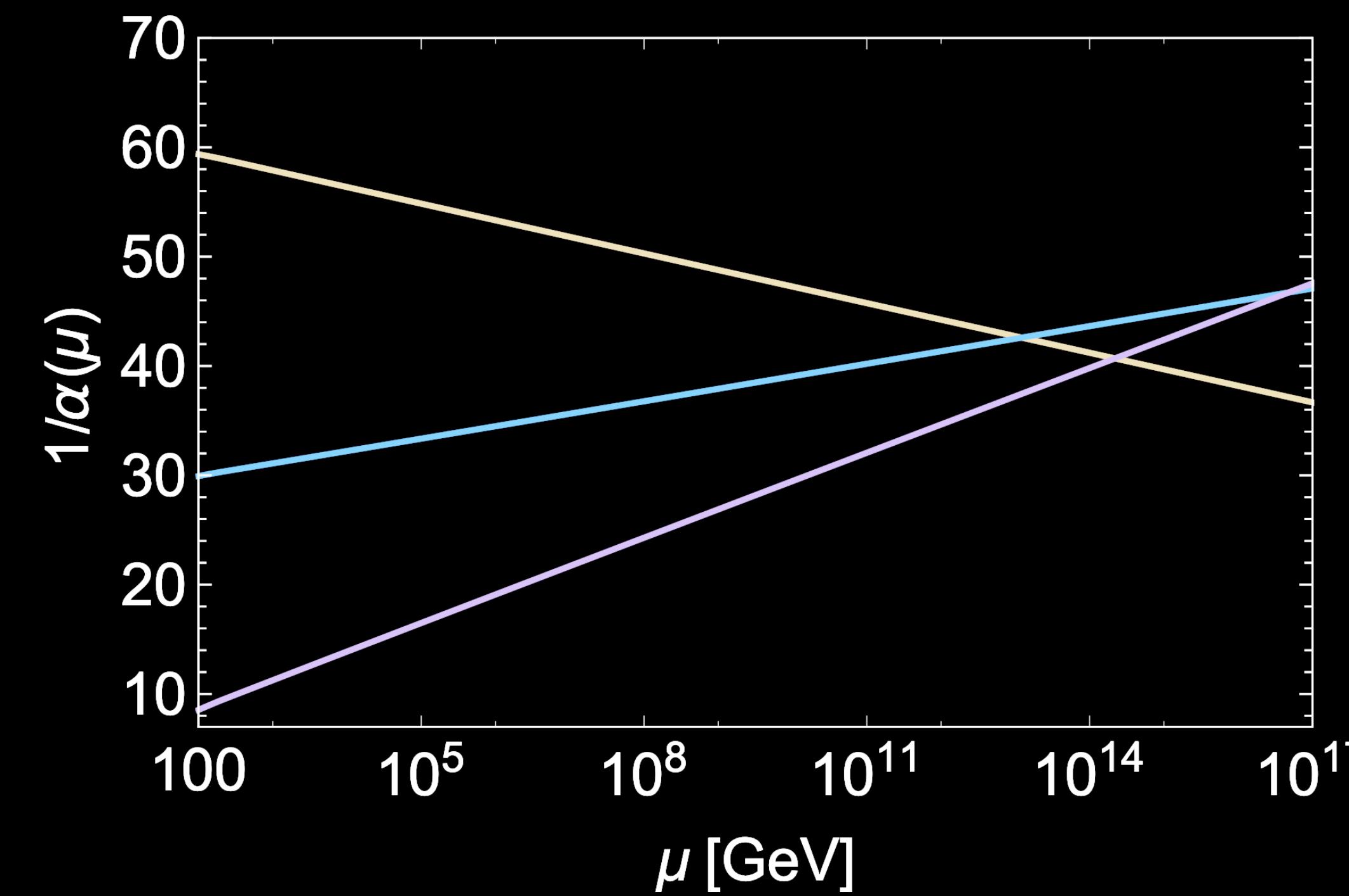
Supersymmetry



Composite Higgs



Unification beyond the Standard Model?



Running of couplings in the Standard Model tantalizingly hints at unification, but the intersection is imperfect & scale too low.

New particles at TeV energies sharpen the prediction & raise the scale: clear targets for a high-energy muon collider, reach to $\sim \sqrt{s}/2$.

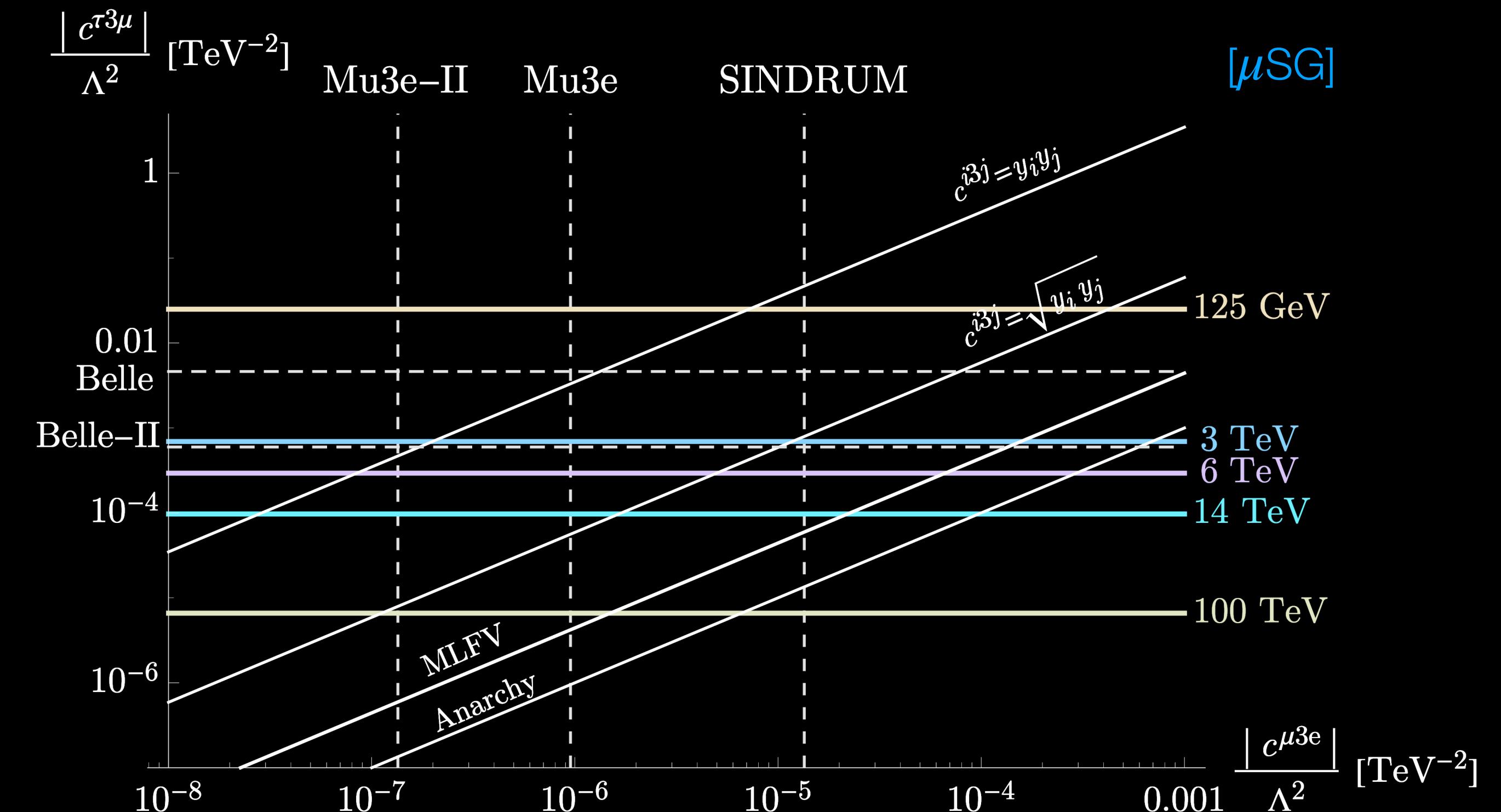
What is the origin of flavor?

The first high-energy accelerator to primarily collide second-generation fermions.

High collision energies provide:

Direct access to hypothetical new particles associated with flavor structure

Indirect access to flavor structure via lepton flavor violating operators



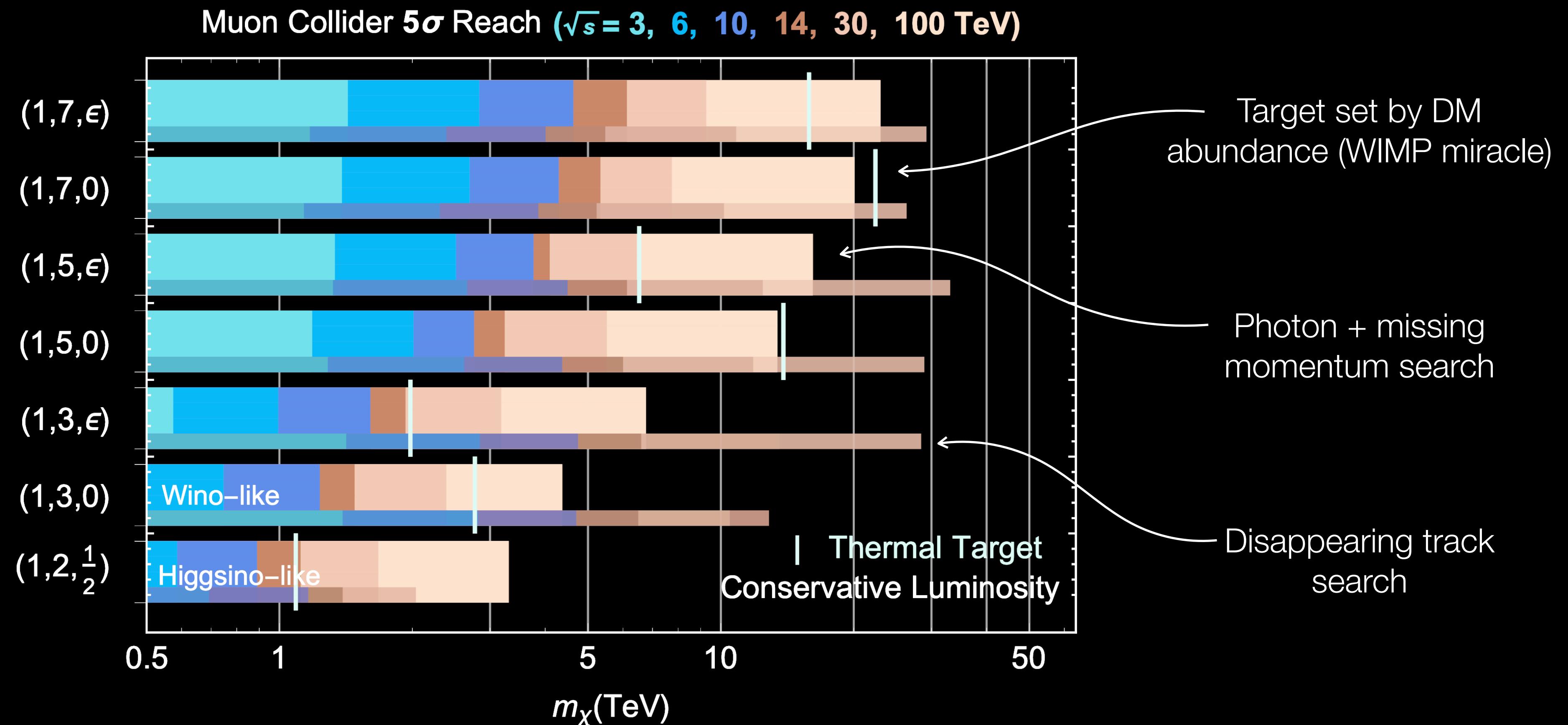
Muon colliders an outstanding probe of explanations for **B flavor anomalies**

[Huang, Queiroz, Rodejohann, 2101.04956; Huang, Sana, Queiroz, Rodejohann, 2103.01617, Asadi, Capdevilla, Cesarotti, Homiller 2104.05720]

What is the nature of dark matter?

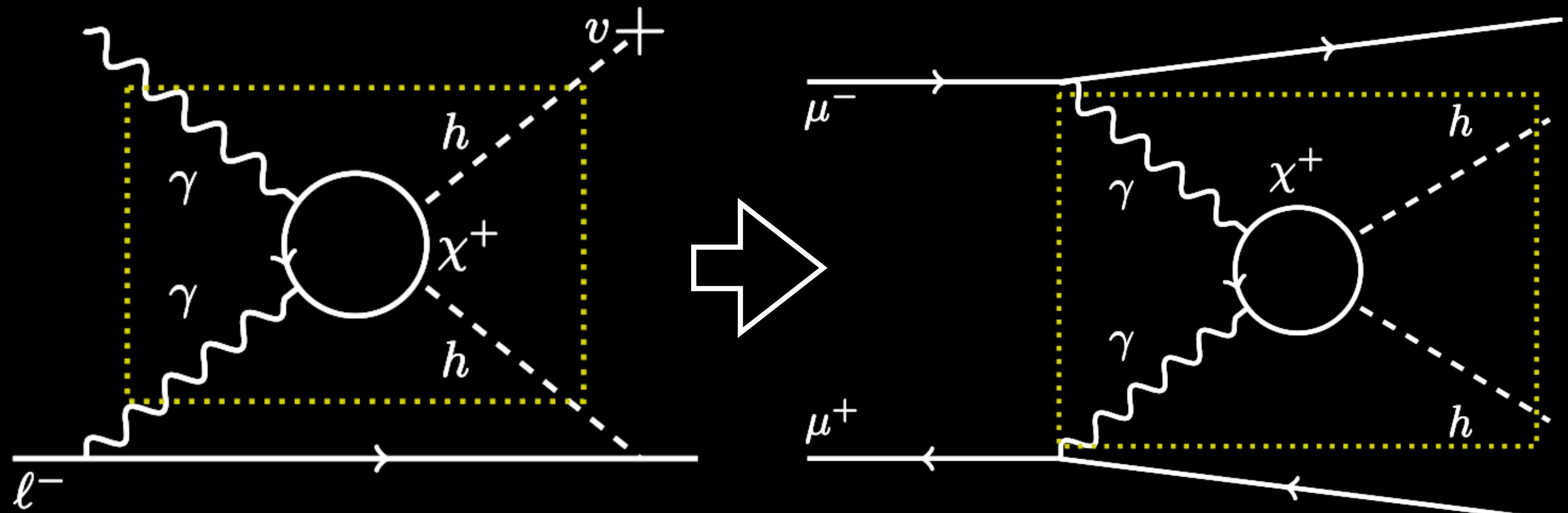
Powerful prospects for a μ C in final states with missing energy:
large electroweak production rates, low backgrounds compared to hadron colliders

“Minimal dark matter”
(Electroweak multiplets
with neutral lightest
particle, abundance set
by SM interactions)

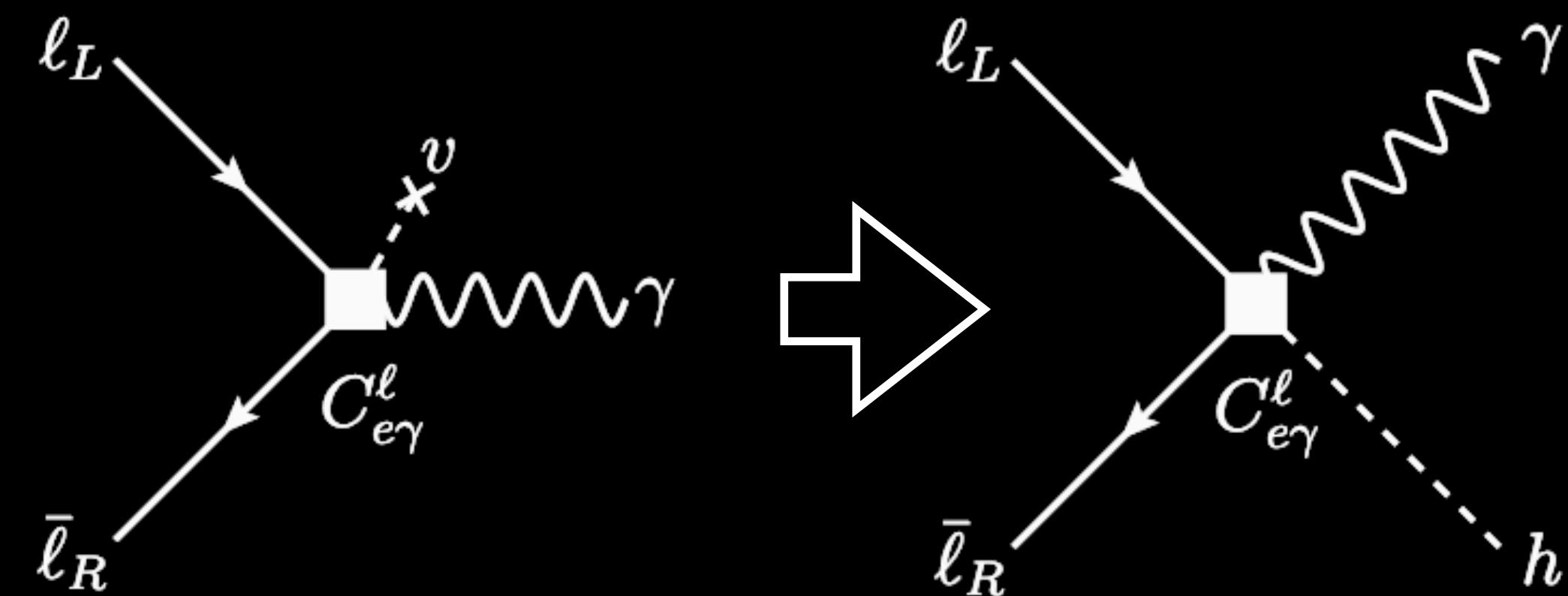


Compelling complementarity

E.g. next-gen. **electron EDM** experiments sensitive to ~ 20 TeV particles in Barr-Zee diagrams; same diagram probed in muon colliders



Any new physics contributions to **Muon g-2** efficiently probed at muon colliders
[Capdevilla, Curtin, Kahn, Krnjaic, 2006.16277; Buttazzo & Paradisi, 2012.02769; Capdevilla, Curtin, Kahn, Krnjaic, 2101.10334; Chen, Wang, Yao 2102.05619; Yin, Yamaguchi 2012.03928]



[Buttazzo & Paradisi, 2012.02769]

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The muons are calling, and we must go.